EuroSTRATAFORM: Three-Dimensional, Moving-Boundary, Integrated- Morphodynamic Models of Sedimentation on Continental Margins

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LONG-TERM GOALS

The long-term goal of this research is to develop moving-boundary, morphodynamic models of continental-margin response to high-amplitude, late-Quaternary changes in sea level (Task **D4**).

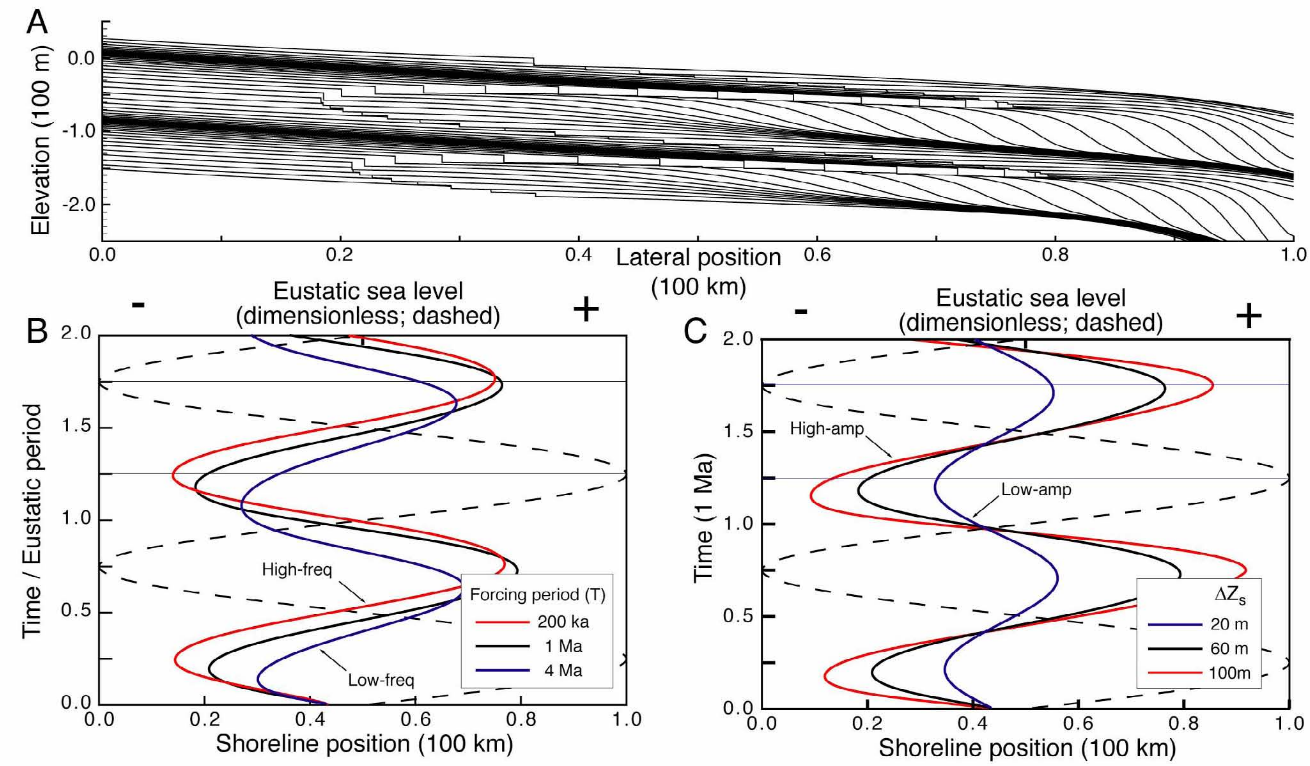

Figure 1. Generic fluviodeltaic response to sea-level cycling in a high-energy basin setting. (A) Representative stratigraphic cross section showing development of compound-clinoform geometries; Amplitude and period of sea-level cycle are A = 30 m and T = 1 Ma, respectively. (C) Frequency dependence of shoreline response to eustatic forcing (A = 30 m). (C) Amplitude dependente of shoreline response to eustatic forcing (T = 1 Ma).

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14. ABSTRACT
The long-term goal of this research is to develop moving-boundary, morphodynamic models of continental-margin response to high-amplitude, late-Quaternary changes in sea level (Task D4).

15. SUBJECT TERMS

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OBJECTIVES

1. Quantify the stratigraphic response of generic, high-energy fluviodeltaic systems to high-amplitude fluctuations in relative sea level, with emphasis on the behavior of the shoreline, the clinoform rollover, and the 'shelf edge'.

2. Investigate the ability of long-term changes in the frequency and magnitude of coastal storms (basin 'energy' relative to fluvial input) to generate significant cycles of shoreline transgression and regression.

3. Analyze theoretically and experimentally how coastal prisms, i.e. the subaerial delta and shoreface, respond to late-Quaternary sea level fall, with emphasis on tracking the moving boundaries (alluvial-basement transition, shoreline, and delta toe) and delineating the basic controls on aggradation and degradation.

4. Begin to explore the potential role of nearshore processes in controlling the behavior (notably the avulsion rate) of distributary channels on the delta plain.

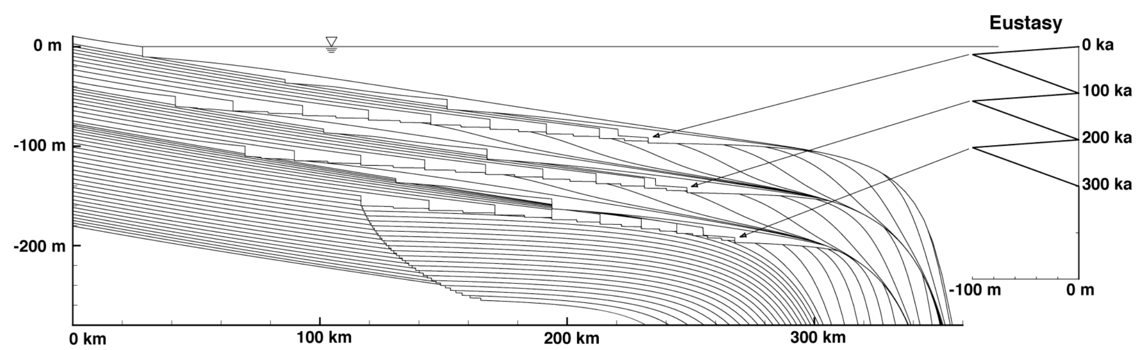

Figure 2. Margin response to three 'sawtooth' cycles of late-Quaternary sea-level change in a high-energy basin setting. Arrows point to lowstand shoreface position; note its separation from the physiographic 'shelf edge'.

APPROACH

· Continued development of morphodynamic model of compound-clinoform evolution in response to subsidence, fluctuations in eustatic sea level, and variations in long-term wave climate of the basin.

· Generalized moving-boundary model of fluviodeltaic sedimentation to (1) allow direct comparison with laboratory-scale experimental data and (2) include wave-driven, 'out-of-plane' longshore sediment dispersal.

WORK COMPLETED

1. Developed a moving-boundary model of fluviodeltaic response to high-amplitude fluctuations in relative sea level in high-energy, shallow-marine settings. Fluvial morphodynamics is diffusive; shallow-marine morphodynamics is depth-dependent (non-linear) advective-diffusive. Fluvial and shallow-marine environments are coupled across a shoreface shock, which is the mathematical embodiment of the surf zone. In addition to sea level cycling, the model is designed to capture long-term fluctuations in wave energy of the receiving basin; such imposed fluctuations are communicated via the morphodynamic parameters and via changes in shoreface geometry and associated sediment storage. The model was used to analyze the fluviodeltaic response to a range of amplitudes and frequencies of eustatic cycling (Fig. 1) and the spatial relationship between last-glacial-maximum (lowstand) shoreline position and the 'shelf edge' (Fig. 2). In addition, the model was used to analyze the stratigraphic response to periodic fluctuations of long-term wave energy over a range of frequencies (Fig. 3).

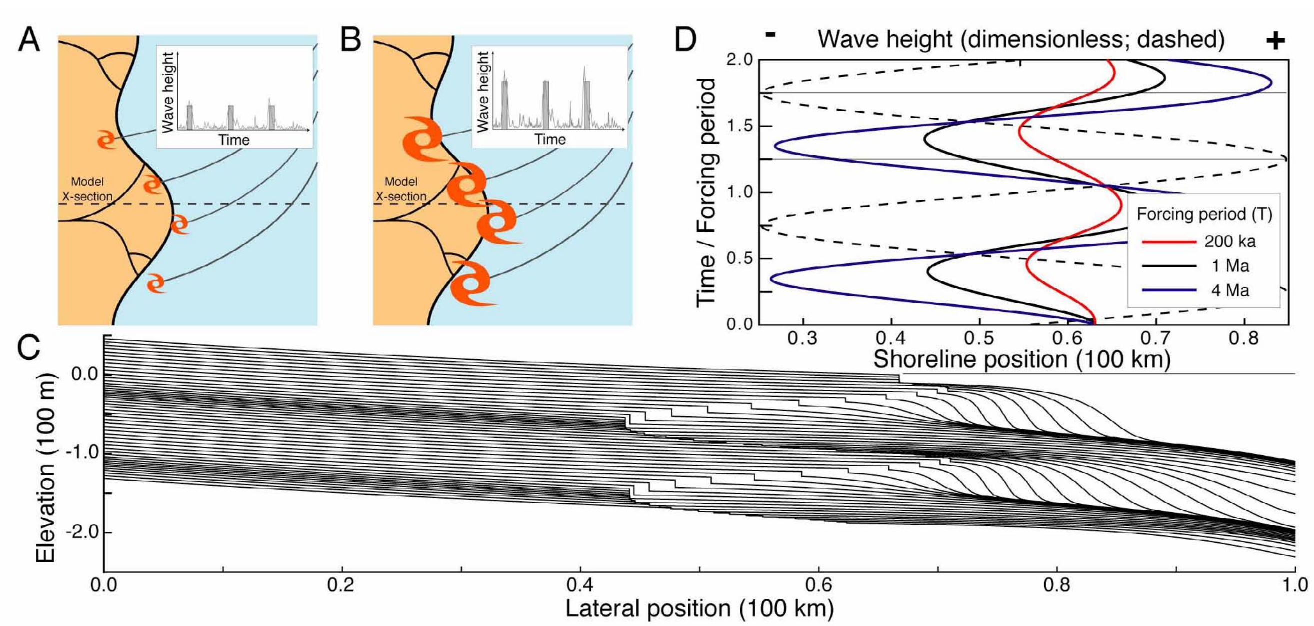

Figure 3. Two cycles of shoreline transgression and regression driven by long-term fluctuations in the intensity (wave height) of coastal storms. Cartoon shows periods of (A) weak and (B) strong characteristic coastal storms. (C) Representative stratigraphic response showing development of compound-clinoform geometries. Note change in shoreface depth during cycles. (D) Dependence of shoreline response to frequency of fluctuations in long-term basin energy.

2. Performed a rigorous exploration, both theoretically and experimentally, of coastal-prism response to falling relative sea level, with emphasis on the basic controls on aggradation and degradation (sequence-boundary formation) (Figs. 4 and 5). The theoretical component of this work involved significant modification of my moving-boundary theory of fluviodeltaic sedimentation to accommodate the non-linear flux relationships that characterize small-scale physical experiments; the resultant morphodynamic model is strongly non-linear. I worked closely with Tetsuji Muto (Nagasaki University) to test the theoretical predictions via an extensive suite of flume experiments.

3. Modified moving-boundary theory of fluviodeltaic sedimentation to capture transport of distributary channel discharge via wave-driven longshore transport (Fig. 6). Model approach is quasi-three-dimensional and couples a cross-sectional treatment of distributary-channel morphodynamics to a plan-view model of longshore transport and associated shoreface progradation. Model was used to quantify the role of longshore sediment dispersal in suppressing distributary-channel avulsion.

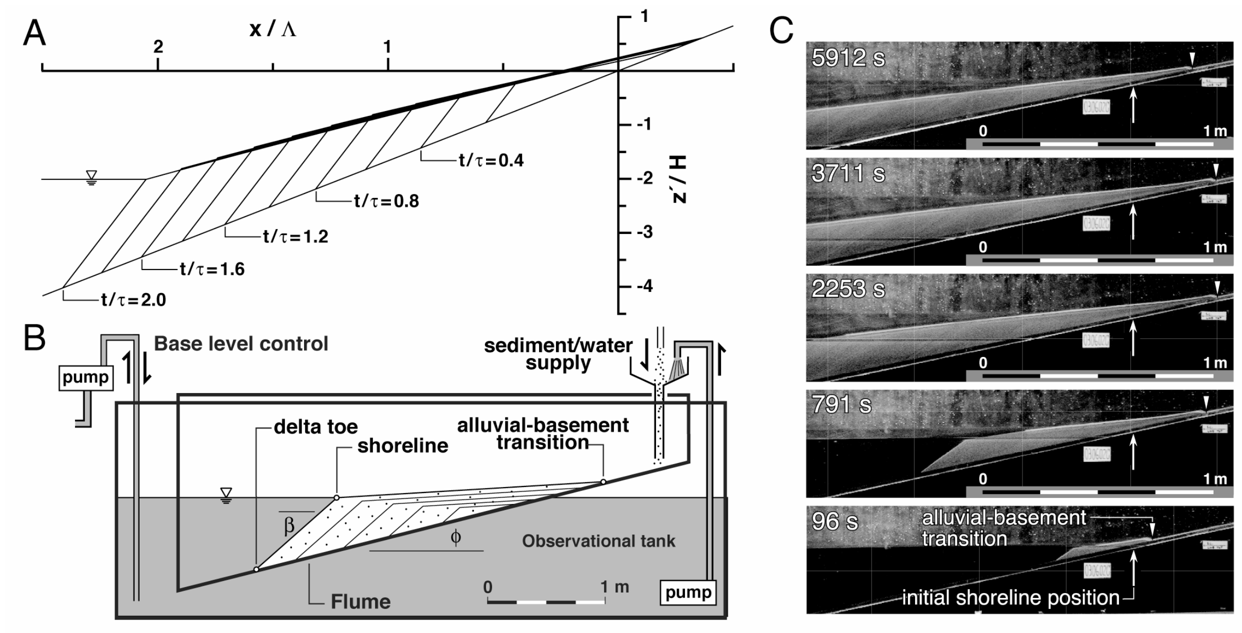

Figure 4. (A) Representative model prediction of coastal-prism response to steady fall in relative sea level. All quantities dimensionless. (B) Schematic of experimental facility used to test theory. (C) Representative response of experimental coastal prism to steady fall in relative sea level. Note transition from onlap to offlap at the alluvial-basement transition. Compare to (A).

RESULTS

1. On high-energy margins, high-amplitude cycles of relative sea level generate stacked sequences of compound-clinoforms (Fig. 1a). For the range of parameter space explored, fluvial incision was minimal, and the majority of erosion during sea level fall can be attributed to beveling by the shoreface; transgressive erosion via shoreface reworking is significant during sea level rise.

2. High-energy fluviodeltaic systems appear to behave as high-pass filters to variable-frequency eustatic forcing (Fig. 1b), with the magnitude of regression/transgression reduced with decreasing forcing frequency. In addition, a strong phase shift develops between shoreline response and eustatic forcing as the period of forcing becomes large relative to the intrinsic system response time, i.e. at ‘low’ frequencies (Fig. 1b). Both the filtering and phase-shifting are similar to behavior predicted by some earlier geometric models, but are strongly at odds with recent theoretical work and supporting ONR-funded experiments on coastal-prism response to sea-level cycling (Swenson, 2005). Shoreline response is relatively insensitive to the amplitude of sea-level forcing (Fig. 1c).

3. In contrast to sequence-stratigraphic theory, the lowstand shoreline and physiographic ‘shelf edge’ can be separated spatially by significant ($10^1 – 10^2$ km) distances in high-energy settings (Fig. 2). This

separation is a direct manifestation of the compound-clinoform geometries that characterize these systems. Throughout sea level fall, the active clinoform rollover remains significantly seaward of the shoreface; merging of the active clinoform rollover with the relict shelf edge rejuvenates margin progradation near lowstand, but the shoreface remains landward of the shelf edge. The sawtooth patterns of sea-level fall and rise accentuate this behavior in late-Quaternary settings (Fig. 2).

4. Model results indicate that physically plausible fluctuations in the long-term wave energy of a margin can drive significant cycles of shoreline transgression and regression (Fig. 3). Fluctuations result from long-term changes to the intensity of coastal storms and their associated wave field. As was the case with eustatic fluctuations (Fig. 1), fluctuations in wave energy generate stacked sequences of compound clinoforms. Intervals of shoreline transgression and regression correspond, at first order, with increasing and decreasing wave energy. Model results suggest that the fluviodeltaic system behaves as a low-pass filter to fluctuations in wave energy, with the amplitude of shoreline migration decreasing with increasing forcing frequency (Fig. 3d). In addition, strong phase lags develop between shoreline response and imposed forcing as the forcing period becomes small relative to the intrinsic system response time. While the stratigraphic response is similar (compare Figs. 1a and 3c), the filtering and phase-shifting of the shoreline response due to long-term fluctuations in wave energy are opposite to those observed for sea level cycling (compare Figs. 1b and 3d).

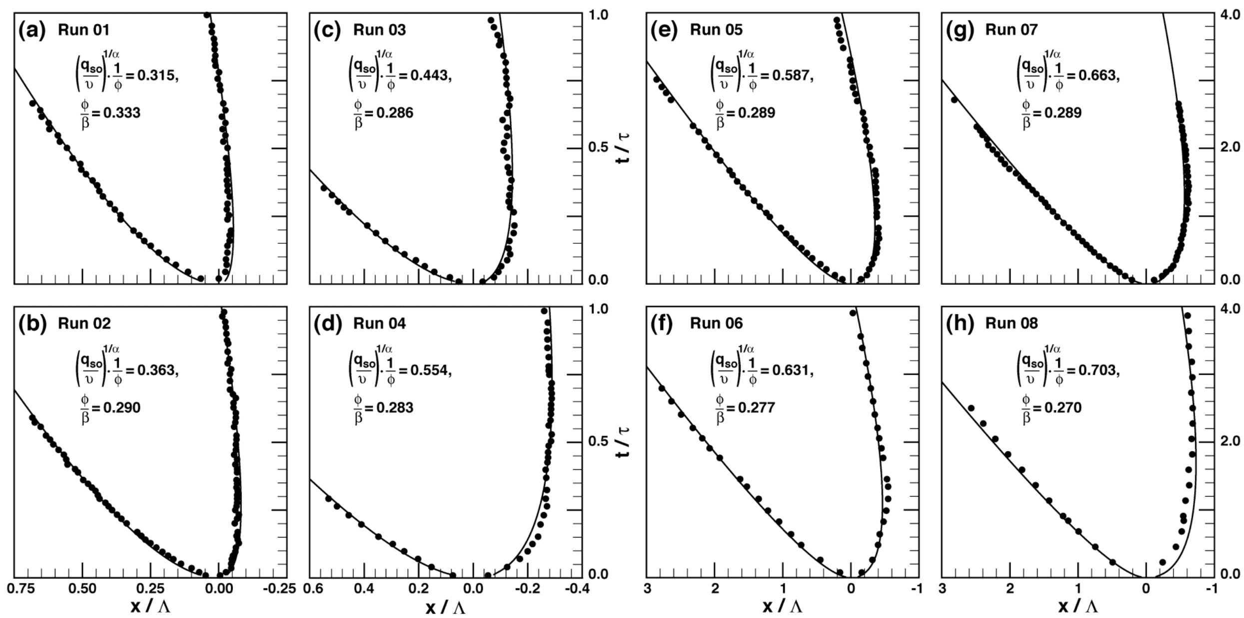

Figure 5. Comparison of moving-boundary theory and flume experiments for coastal-prism response to steadily falling sea level. Panels (a) – (f) represent a systematic exploration of the two-dimensional parameter space that describes system behavior. In each panel, solid curves are the predicted evolution of the shoreline and alluvial-basement transition; closed circles are experimental data. All quantities dimensionless.

5. Coastal-prism response to steadily falling sea level shows a three-stage evolution: The prism first expands landward and seaward by coastal onlap and shoreline regression, respectively, while remaining entirely aggradational. With sustained sea level fall and prism lengthening, the shoreline eventually becomes erosional, and a zone of degradation expands landward and seaward, tracking the

regressive shoreline. The transition from coastal onlap to offlap at the alluvial-basement transition signals the arrival of this degradation zone at the upstream boundary of the alluvial system. From this time onward, the coastal prism is entirely degradational but continues to expand seaward via subaqueous accretion to the delta front (Figs 4a and 4c). Moving-boundary theory suggests that two dimensionless numbers control the durations of each stage in this evolution. An extensive set of physical experiments (Fig. 4b), which explored this two-dimensional parameter space, gives strong support to the theoretical predictions (Fig. 5). The overarching conclusion of this combined theoretical and experimental study is that alluvial river systems can remain aggradational during sea-level fall for geologically significant time intervals and, further, that the duration of aggradation is sensitive to the system parameters, particularly sediment supply and rate of sea level fall. These predictions contradict existing sequence-stratigraphic models, which predict alluvial degradation throughout sea level fall.

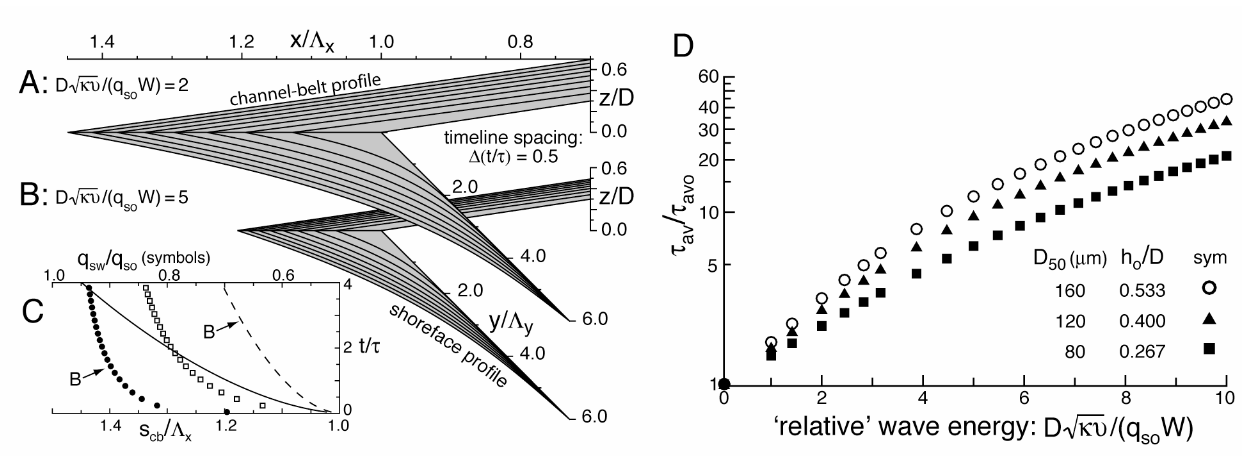

Figure 6. Morphodynamic modeling of distributary-channel aggradation/extension and associated shoreface progradation showing sensitivity to an increase in relative wave energy by a factor of 2.5 between (A) and (B). (C) Evolution of channel length s_{cb} and sediment extraction by wave energy q_{sw}. (D) Interavulsion period τ_{av} as a function of relative wave energy; normalizing factor τ_{avo} is the interavulsion period in the limit of vanishing relative wave energy.

6. Wave-driven longshore sediment dispersal can effectively suppress distributary-channel avulsion. An increase in the wave energy relative to fluvial input of sediment and water increases longshore sediment dispersal, thereby decreasing the rate of distributary-channel extension and associated aggradation (Fig. 6a-c). The reduction in aggradation rate increases the time interval required for the channel-belt to reach the critical superelevation above the coastal plain that is necessary for avulsion to proceed (Fig. 6d). Larger-scale processes, e.g. interference of multiple channels or 'upstream' controls, ultimately overwhelm the effects of longshore dispersal and force avulsion.

IMPACT/APPLICATIONS

Model results have important implications for reconstructing the history of climate and tectonics from shoreline trajectories preserved in the rock record. Fluctuations in eustatic sea level and long-term wave energy are capable of generating remarkably similar sequences of compound clinoforms, thereby introducing an additional layer of non-uniqueness to the difficult inverse problem of interpreting the stratigraphic record. The frequency dependence of shoreline response to these two forms of allogenic forcing are profoundly different; if sufficient chronostratigraphic resolution is available, this difference

may provide a mechanism for deciphering one forcing mechanism from the other. Model results also challenge basic predictions of sequence-stratigraphic models. Notably, the physiographic 'shelf edge' does not necessarily correspond to the lowstand shoreline and sea level fall need not result in large-scale fluvial degradation.

RELATED PROJECTS

Theoretical advances reported here were an integral part of a recent NSF-sponsored working group entitled 'Novel methods for modeling the surface evolution of geomorphic interfaces', which met at the Massachusetts Institute of Technology in April 2004 and July 2005.

The modeling of compound-clinoform response to sea-level forcing has stimulated collaboration between myself and Torbjorn Tornqvist (Tulane Univ.) on the spatial relationship between last-glacial-maximum shoreline and the physiographic shelf edge. We will resubmit a proposal to NSF in February 2006.

Work with Tetsuji Muto (Nagasaki Univ.) on coastal-prism response to falling sea level has generated several collaborative projects on related topics involving experimental tests of fluviodeltaic theory.

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